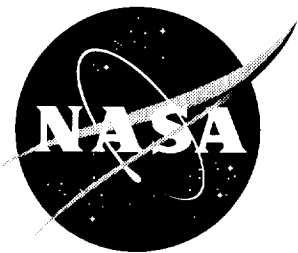


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Low-Cost Quality Control and Nondestructive Evaluation Technologies for General Aviation Structures

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I. Abstract

NASA's Advanced General Aviation Transport Experiments (AGATE) Program has as a goal to reduce the overall cost of producing private general aviation aircraft while maintaining the safety of these aircraft. In order to successfully meet this goal it is necessary to develop nondestructive inspection techniques which will facilitate the production of the materials used in these aircraft and assure the quality necessary to maintain airworthiness. This paper will discuss a particular class of general aviation materials and several nondestructive inspection techniques that have proven effective for making these inspections. Additionally, this paper will discuss the investigation and application of other commercially available quality control techniques applicable to these structures.

II. Introduction

A major factor in competitively producing an affordable certified private aircraft is developing materials that can be used to safely and cost-effectively form the fuselage and wings. One candidate material, which has the potential to meet this challenge, is fiberglass. Fiberglass is a composite material with glass fibers suspended in an epoxy resin. To increase the stiffness of this material, thin layers of fiberglass skin can be used to sandwich a core material, such as low-density foam.

In order to reduce the production costs of fiberglass / foam composites it is necessary to develop nondestructive testing techniques which can ensure the quality of these materials during the manufacturing process as well as provide cost-effective inspection methods during routine maintenance for the life of the structure.

Currently most general aviation manufactures use visual, coin-tap or ultrasonic inspection methods (or some combination thereof) for inspection these materials. While these techniques can be quite effective in locating disbonds they have some potential drawbacks. All require extensive training and significant expertise for accurate interpretation of the results. Additionally, ultrasonic inspection equipment can be expensive to purchase and is typically slow for large area measurements.

This paper will discuss in detail two low-cost techniques that can meet the challenges of the inspection of these materials for differing types of defects. The first technique is a low-cost thermal method which utilized thermochromic liquid crystal sheet to sense temperature changes induced by actively heating the material being inspected. The second technique is called shadow moiré. This technique uses optical methods to detect small displacements in the material surface due to subsurface delaminations. Both of these methods allow large areas to be inspected quickly. Additionally, the thermal method also provides size and shape information of the defects found.

Experimental results will be provided for a series of test samples, and a procedure for implementing the first of the technologies, mentioned above, will be provided. Currently, a procedure for the second technology has not been developed.

III. Problem Definition

Two general classes of inspection scenarios exist for fuselage and wing materials in the general aviation aircraft investigated during this research. The structural bonding of fiberglass composite skins,

also called secondary bonding, is used wherever it is necessary to join two structural elements together after the individual parts have been cured. For secondary bonds disbonding is also a major quality control and inservice inspection concern.

The second area of interest is core stiffened, sandwich materials. These are typically used to provide stiff, lightweight fuselage and wing panels and consist of low-density open-celled foam sandwiched between layers of fiberglass composite skin. Disbonding between the fiberglass skin and the foam core can weaken the structure and is therefore of concern both for manufacturing quality control and for inservice inspection.

Since each of these types of structures present a different problem from an nondestructive inspection point-of-view they were addressed separately in this investigation.

IV. Experimental Techniques

Two low-cost, rapid nondestructive inspection methods were explored using experimental techniques. The first method is a low-cost thermal technique which utilized thermochromic liquid crystal sheet to sense temperature changes induced by actively heating the material being inspected. The second method called shadow moiré, uses optical methods to detect small displacements in the material surface due to subsurface delaminations.

A. Thermochromic Liquid Crystal (TLC) Sheets

Infrared (IR) thermography has been used extensively for the detection of defects in bonded structures. Typical thermography systems employ an IR radiometer (or simply an IR camera) which measures the thermal radiation, in a particular wavelength range, emitted by a surface and converts this to a measure of the surface temperature. Applications of this technology for nondestructive evaluation (NDE) usually consist of actively heating the material's surface a few degrees centigrade. The spatial and temporal responses of the material to the external application of heat can then be recorded and used to calculate variations in material properties, which can be indicative of defects in the material.¹ A disadvantage of this technology for application to general aviation materials is the cost. Typical IR radiometers cost approximately \$60,000.00 (U.S.). Add to this the cost of an image processor for data acquisition and analysis, and a heat source which must be synchronized with the data acquisition for accurate temporal information and this can boost the cost of a complete thermal NDE system to \$100,000.00 (U.S.) or more.

One technology that takes advantage of the effectiveness of thermal NDE and has proved particularly cost-effective in the inspection of defects in secondary bonds in fiberglass skins is thermochromic liquid crystal sheets. TLC sheets are optically active mixtures of organic chemicals that react to changes in temperature by changing color. TLC sheets show color by selectively reflecting incident white light. These typically turn from colorless (black against a black background) to red at a given temperature and, as the temperature increases pass through the other colors of the visible spectrum in sequence (orange, yellow, green, blue, violet) before turning colorless (black) again at a higher temperature still.² Typically, the TLC sheets can be controlled at time of manufacture to have a pre-defined mid-green temperature and a specific full color change bandwidth. The TLC sheets can be obtained commercially in a number of different forms such as unsealed liquids, microencapsulated coating formulations and coated sheets. For the studies discussed here, the coated sheets were used exclusively, although some initial investigations were made into using microencapsulated coating formulations. The coated sheets are available commercially and consist of a thin film of liquid crystals sandwiched between a transparent polymer substrate and a black absorbing background.

There are a number of advantages to using the TLC sheets over other NDE methods. First, is the cost. The TLC sheets are quite inexpensive, costing approximately \$25.00 (U.S.) for a 12in. by 12in. reusable sheet. Second, the inspection is rapid, typically taking only a few seconds. After application of the sheet to the surface being inspected, a small amount of heat is injected through the sheet causing a temperature rise in both the sheet and the structure. If a delamination is present a temperature gradient will develop and be evident by nonuniform color changes in the TLC sheet. A detailed discussion of the experimental procedure is presented in Section VIII of this paper. If

desired, the results of the inspection can be recorded using a conventional camera, video or digital camera and then archived for later reference.

Additionally, the test is totally nondestructive, as typical temperature changes of the surface are less than 5°C, leaving the part under inspection undamaged. Further, the TLC sheets are very flexible (typical substrate is 0.005 in. Mylar) which allows conformance to many part shapes, and the sheets can be cut to match the shape of specific parts. Finally, the TLC sheets provide clear indications of the size and location of the disbond areas in the part, which makes training and interpretation simple.

To use the TLC sheets effectively for disbond detection it is necessary to induce a small temperature gradient between the bonded and disbanded regions of the parts being inspected. This can be done by actively injecting heat into the parts while observing the temperature changes that occur using the TLC sheets. For the TLC sheets to accurately measure variations in the temperature of the part, the sheets must be in good thermal contact with the part surface. This can be achieved a number of ways. The TLC sheets are available with a self-adhesive backing material that will facilitate application. It has been found that while this adhesive is convenient, after 4 or 5 applications of the same sheet most of the adhesive is gone and therefore limited the life of the TLC sheets. Further, the self-adhesive sheet can leave adhesive residue on the part under inspection, thus requiring additional post-inspection clean up. Another alternative is to obtain TLC sheets with no backing materials and use a coupling material to assure good thermal contact between the sheet and the surface. One material that is quite effective is standard ultrasonic coupling jell. Small amounts of this jell are put the corners of the sheet and then a roller or squeegee is used to evenly distribute the jell. Even distribution proves to be quite important for accurate and easy interpretation of the results. Likewise, this alternative also requires some post-inspection clean up. A final alternative for coupling the sheet to the skin, involves construction of a vacuum bag system that will allow the area between the TLC sheet and the part face to be evacuated to provide good thermal contact. Additionally, it may be possible to implement a system whereby the TLC sheet is built into the vacuum bag used in the initial curing of the parts and thus allow an initial quality control inspection to be performed during the manufacturing process. While this potential exists, it was not investigated during this study.

B. Shadow Moiré Instrument

Optical interference techniques such as shearography and holography have been used extensively for nondestructive evaluation. These techniques have proved quite useful for both flaw detection and material characterization in numerous materials.³ Shearography is sensitive to derivatives of the out-of-plane displacement of a body under load, while other full-field methods such as holography typically contour the surface displacement directly.⁴ Both of these techniques require some external load be applied to the part under inspection to produce a deformation of the target surface which is then referenced to an undeformed interference pattern previously acquired and stored electronically. The external load can be applied in any one of a number of ways such as heating, vibration, pressurization or mechanical loading. These techniques are typically quite expensive, with commercial systems easily costing \$100,000 (U.S.) or more. This expense has been a limiting factor in their application to general aviation materials.

Another optical technique, which has proved to be both low-cost and effective for the detection of disbonding between fiberglass skins and foam core material, is the shadow moiré method. This method uses optical techniques to detect small displacements in a surface which is not experiencing loading. In the case of fiberglass skins bonded to foam core, these displacements are due to disbonds that occur between the skin and core. In the shadow moiré method, low-frequency beat or moiré patterns can be observed when light leaving a source passes through an optical grating with some fixed period P , at an angle Θ from the normal. The light is then reflected from the surface of the test article back through the grating and viewed at from different direction. Since two rays of light leaving the source can have different path lengths on reflection, due to the presence of the grating, a perceived interference pattern occurs⁵. Figure 1 shows a schematic of the shadow moiré inspection method.

If the surface is flat and parallel to the grating, the pattern seen will be a regular spacing of fringes. The fringe-to-fringe contour interval can be defined as:

$$\Delta Z = P / \tan \Theta .$$

On the other hand, if surface deformation is present, there will be an additional localized path length change and the resulting in changes in the localized fringe density. In severe deformation cases the fringes tend to form rings around the deformation.

The shadow moiré method has a number of advantages as an NDE technique for general aviation aircraft materials. The foremost advantage compared to other optical techniques is the cost. Commercial shadow moiré devices can be purchased for a few hundred dollars (U.S.) or it is possible to construct a device for much less. With the recent improvements in laser printer technology adequate gratings can be printed directly onto transparency film and a simple home video camera light with an appropriate slit attached can serve as the light source. Figure 1 shows a charge coupled device (CCD) camera being used to digitally record the images for future reference, but this is only necessary if digital data storage is an inspection requirement. Visual inspection of the resulting fringe pattern is possible and recording if necessary can be done by any optical means desired (for example a Polaroid™ camera).

Because the shadow moiré method requires that the surface being inspected be a diffuse reflector, depending on the surface coating, it may be necessary to lightly coat the surface with something such as talcum powder. In the case of the samples inspected during this study, it was not necessary to perform any additional surface coating other than the standard gelcoat already present.

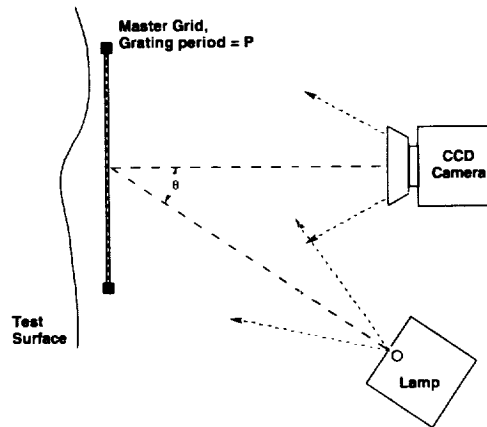


Figure 1. Schematic of inspection using shadow moiré method.

V. Results

Inspections were performed using both thermochromic liquid crystal sheets and the shadow moiré optical inspection method on samples fabricated with delaminations in secondary bonds and in fiberglass skins bonded to foam cores.

A. Secondary bondline inspection using Thermochromic liquid crystal sheets

To investigate the application of TLC sheets to the detection of disbonding in secondary fiberglass skins, a sample was constructed by Stoddard Hamilton Aircraft, Inc. consisting of two fiberglass skins, each of 4 plies thickness (each ply being approximately 0.3 mm thick), bonded together. At the bond line, artificial disbands were created during the bonding process. A schematic of the size and shape of the disbond pattern is shown in Figure 2. This sample was inspected using a TLC sheet with a mid-green temperature of 35°C and a temperature bandwidth of 5°C. Heat was injected directly through the sheet using a 500-Watt quartz lamp. The TLC sheet was heated until it

experienced a complete color change, the heat was then removed and the sheet was observed during the cooling process. During the inspection, care must be taken to ensure relatively even heating over the inspection area. This can be accomplished by observing the uniformity of the color changes in the TLC sheet. Because the presence of a disbond retards the flow of heat into the panel at that location, disbonds appear as hot spots on the TLC sheet. Figure 3 shows a photograph of the sheet several seconds after removal of the heat. The disbonds, which are clearly visible in the gray scale image as light colored regions, appear as distinct color changes in the actual TLC sheet. Depending on the fiberglass thickness, the disbond indications will remain visible for up to several minutes after the removal of heating device.

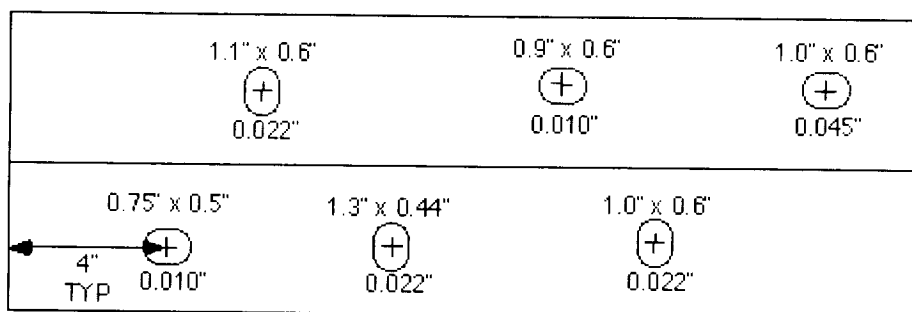


Figure 2. Schematic of secondary bond sample showing size and location of imbedded disbonds

Figure 4(a) shows a field application of this technique to an inservice repair of the bondline between the upper wing skin and spar. Unfortunately, no results were obtained during this infield inspection due to high ambient temperatures, outside the operational range of the TLC sheet available at the time. This highlights the need to be careful in selecting TLC sheets with the proper mid-green temperature and full color change bandwidth for a given application.

An alternate application mechanism for this method is shown in Figure 4(b). Here a commercially available device, designed for medical imaging of body temperatures that utilize the TLC sheets, has been modified to include a quartz lamp heat source. The cost of this device is approximately \$4,000. One advantage of this device is that it eliminates the need for coupling, by using TLC sheets with a highly compliant rubber substrate and then using high-pressure air to hold the sheet tightly to the part being inspected. This device was used successfully to image both the main fuselage bond and the wing to spar bond at Stoddard Hamilton Aircraft, Inc. manufacturing facilities in Arlington, Washington. No mechanism was available at the time to record images of the results.

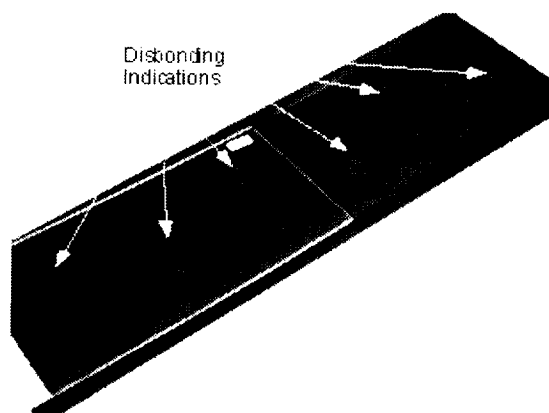
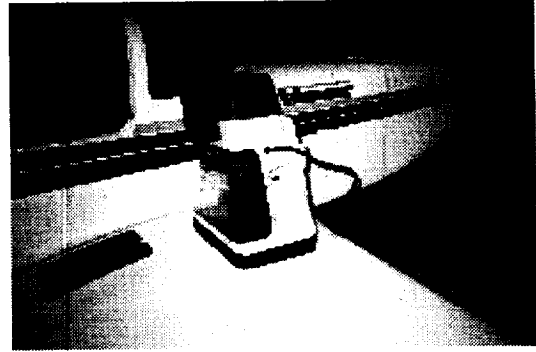


Figure 3. Photograph of the disbonding in secondary bond sample using TLC sheets. Disbonds appear as oblong light colored areas in image.



(a)



(b)

Figure 4. Photographs of TLC sheets being used in (a) the field inspection of a disbonded upper wing skin and (b) as part of a modified commercial medical device adapted for secondary bond inspections.

B. Fiberglass to foam bond inspection using shadow moiré technique

To investigate the shadow moiré method of inspecting skin to foam disbonding, a series of panels were constructed with imbedded disbands of various sizes and locations. Disbonding was achieved by removing a small amount of the foam core material at the bondline before bonding. Then the resulting void was covered with Mylar, to prevent epoxy resin from filling the cavity, and the skin was bonded to the foam core using normal fabrication techniques. Figure 5 shows a schematic of one of these samples. A total of four samples were examined, two of which contained a known pattern of defects and two of which the defect pattern was not disclosed to the inspector. Figure 6 shows a representative image of the results for one defect in one of the samples. Using the shadow moiré method, all the defects in both the known and unknown samples were successfully detected.

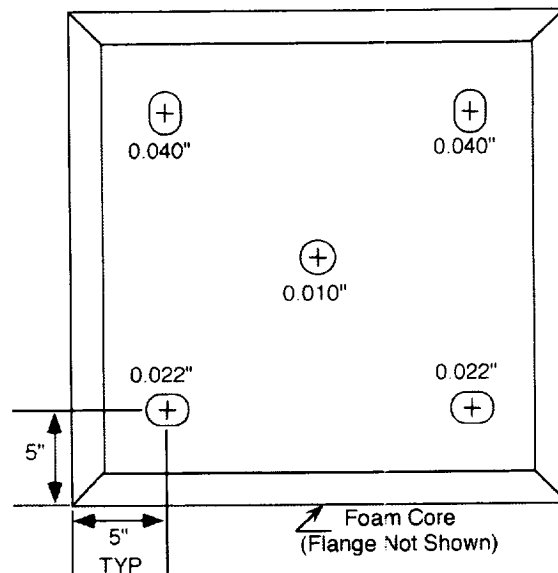


Figure 5. Schematic of foam core disbonding sample created for testing shadow moiré technique.



Figure 6. Representative image using shadow moiré technique of defect in foam core disbonding sample.

VI. Conclusions

Several low-cost NDE techniques have been developed for application to general aviation materials and structures. These techniques include thermochromic liquid crystal sheets and the shadow moiré optical technique. Each of these have been shown to be applicable to different general aviation problems, which indicates that currently no single NDE technique is able to completely characterize general aviation materials for all critical flaws. But it is possible to combine techniques based on specific materials and flaws of interest to successfully inspect these materials.

Several other techniques that are currently under development in the field of nondestructive testing also appear to hold promise of providing alternate low-cost inspection tools for the general aviation community. These techniques include an infrared system where heat is applied using a moving line and a linear array of IR detectors is used to record the surface temperature at a fixed distance behind the line. Further, the use of imbedded sensors into composite materials has shown promise of providing significant information about the material during and after the manufacturing process.⁶ As use of these imbedded sensors increase, the cost should become competitive with other NDE techniques.

VII. Appendix A – Other NDE Technologies Explored

Additionally other NDE technologies have been investigated for application to the detection of disbonding between fiberglass skins and foam core material. These technologies consisted of ultrasonic, infrared thermal imaging, eddy current, laser shearography and x-ray.

Typical ultrasonic aerospace C-Scan equipment was not explored due to acquisition cost, size, setup, complexity and scan rates. However, portable single sided hand held equipment was found to be affordable, prices being in the \$8,000 to \$10,000 range. Unfortunately, it required significant operator interpretation and intense training to produce repeatable, consistent results. It also left the determination of scan grids up to the operator which, coupled with the small probe size, yielded a large margin for error in missing a defect area. One hand held unit produced by McDonnell Douglas known as the MAUS III looked promising although was not demonstrated due to availability and initial acquisition costs starting at approximately \$120,000.

Numerous infrared camera suppliers were contacted and asked to demonstrate their equipment on sample defect test panels. The resulting raw images from the different cameras were all quite similar, but less than acceptable providing little or no indications of damage or delamination. This appears to be mainly due to the low density of the foam and honeycomb core materials thus not permitting sufficient

temperature gradients to develop over areas of delamination. However, as discussed earlier, with image processing and a synchronized heat source results were generally enhanced but not without substantially higher acquisition costs and added inspection complexity.

A local supplier and manufacturer of eddy current testing equipment was visited and was also supplied sample defect test panels on which their equipment was demonstrated. This supplier was recommended as the leader in this technology, however the use of eddy current equipment relies on conductive materials and therefore proved inadequate in testing on fiberglass and low density foam sandwich core composite structure. This technology would probably work better on graphite construction. The handheld units are affordable, starting at approximately \$6,000, and exhibit the same operator characteristics as the handheld ultrasonic units.

Advanced laser shearography as well as x-ray equipment was briefly investigated. Due to high acquisition costs, minimal suppliers, safety concerns with operator personnel as well as facility and containment also adding to implementation costs, further demonstrations and investigations were not conducted.

VIII. Appendix B – Procedures for Implementing LC Sheet Inspection

1. Purpose

- a) Use this procedure to do an inspection for disbonding between two fiberglass skins, or between a fiberglass skin and another fiberglass structural member with liquid crystal sheets that are sensitive to temperature differences.
- b) It is necessary to heat the part being inspected. There is no limit to the number of heat cycles so the heat can be applied frequently to the part through the liquid crystal sheet.
- c) This procedure gives instructions for couplant attachment of the liquid crystal sheets.

Note: Other attachment methods are possible, but will not be addressed in this procedure.

- d) This procedure can be used when the temperature of the part, before the inspection, is between 40° F (4° C) and 90° F (32° C)

2. Equipment

a) Liquid Crystal Sheets

- (1) Use liquid crystal sheets made from microencapsulated liquid crystals attached to a Mylar substrate.
- (2) Liquid crystal sheets specified below were used to help prepare this procedure.
 - (a) R30C5W
R35C5W
R40C5W
All manufactured by Hallcrest, Inc.

b) Heat Source

- (1) A quartz lamp, with a 500-watt output, was used as a heat source.
- (2) Other heat sources, such as blow dryers or heat guns, can also be used.

- c) Couplant
 - (1) Grease
 - (2) Thick ultrasonic couplant
 - (3) Honey

3. Preparation for Inspection

- a) Prepare the aircraft (or part) as follows:
 - (1) Get access to the inspection areas.
 - (2) Remove loose paint, dirt, grease and moisture from the surface of the part to be examined. These can give incorrect indications.
- b) Use the applicable liquid crystal sheet
 - (1) Measure the temperature of the part. This can also be estimated from the ambient room temperature, if the part is not exposed to direct sunlight.
 - (2) Use a liquid crystal sheet that has an “initial temperature change” that is at least 4° F (2° C) higher than the temperature of the part.

4. Inspection Procedure

- a) Apply a small amount (approximately 1/8 inch (3mm) diameter) of couplant (see section 2c) to the corners and center of the liquid crystal sheet on the backside of the sheet (opposite the shiny side). A couplant that has the consistency of honey must be used.

Note: The couplant is used to hold the sheet in contact with the surface.

- b) Put the liquid crystal sheet at a corner of the inspection surface.
- c) Use a cylindrical roller (paint roller or equivalent) to remove air bubbles and make the liquid crystal sheet attach smoothly to the inspection surface. Rolling from the outer edges inward (to keep as much of the couplant from squeezing out the edge of the sheet) can be advantageous.
- d) Apply heat to the part through the liquid crystal sheet until the full liquid crystal sheet becomes blue in color. Be careful not to keep the lamp too close to the part during heating, this will cause rapid localized heating of the liquid crystal sheet and will make uniform heating difficult.

Note: Do not apply enough heat to cause the liquid crystals to change from black, through its full color range and become black again. This could damage the liquid crystal sheet and impair results.

- e) Monitor the liquid crystal sheet both during the heating and during the cooling. Make sure that the heat is applied equally to the entire liquid crystal sheet surface.
- f) If the liquid crystal sheet changes color equally over the full sheet, and no small areas of different color are visible, the do steps 4c through 4e two more times to make sure that there is no disbonding in the part

being inspected. Permit the liquid crystal sheet to cool each time (change to initial color) before reapplying heat.

- g) Frequently use the roller to remove air bubbles that occur below the liquid crystal sheets as these can impair results.
- h) Identify disbond areas with the liquid crystal sheets. Disbonded areas will have a different color than areas with good bonding. Typically this color change will be most noticeable during the cooling phase. These areas tend to cool more slowly than the surrounding areas and thus color changes remain visible for longer periods of time.
- i) Use an approved pencil (or marker) to make a mark on the surface of the inspection part in the general area of the indication.
- j) Move liquid crystal sheet to the next adjacent inspection position.
- k) Apply more couplant if necessary. Make sure it is only applied to the corners and center of the liquid crystal sheet
- l) Do steps 4c through 4i again until the entire inspection surface has been examined.

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